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US Army Corps
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ENGINEERING AND DESIGN

Chemical Grouting

ENGINEER MANUAL

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	Engineering and Design CHEMICAL GROUTING	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Engineering and Design
CHEMICAL GROUTING

1. Purpose. This manual provides information and guidance for the investigation and selection of materials, equipment, and methods to be used in chemical grouting in connection with construction projects.

2. Applicability. This manual is applicable to all HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities having military programs and/or civil works responsibilities.

FOR THE COMMANDER:

R. C. Johns

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Colonel, Corps of Engineers
Chief of Staff

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Chapter 1
Introduction

1-1. Purpose

This manual provides information and guidance for the investigation and selection of materials, equipment, and methods to be used in chemical grouting in connection with construction projects. Elements discussed include types of chemical grout materials, grouting equipment and methods, planning of chemical grouting operations, and specifications. Emphasis is placed on the unique characteristics of chemical grouts that benefit hydraulic structures. Uses of conventional portland-cement-based grouts and microfine-cement grouts are not included here, but are discussed in Engineer Manual (EM) 1110-2-3506, Grouting Technology.

1-2. Applicability

This manual is applicable to all HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities having military programs and/or civil works responsibilities.

1-3. References

References are listed in Appendix A. The most current versions of all references listed in Appendix A should be maintained in all districts and divisions having civil works responsibilities. The references should be maintained in a location readily accessible to those persons assigned the responsibility for chemical-grouting investigations and chemical grouting in construction.

1-4. Definitions

Terms used this document are defined in Appendix B.

1-5. Chemical Grout and Grouting

a. Chemical grouts. Chemical grouts are injected into voids as solutions, in contrast to cementitious grouts, which are suspensions of particles in a fluid medium. Chemical grouts react after a predetermined time to form a solid, semisolid, or gel. The distinction between chemical and cementitious grouts is arbitrary in that some particulate grouts are made up of suspension of microfine cement with particles generally less than 10 μm in diameter. The distinction is further complicated by the development of chemical grouts that have particles that are 10 to 15 nm in diameter. Grouts have been formulated that are mixtures of particulate materials in chemical grouts with the particulate materials themselves being capable of solidifying reactions. Grouts discussed in this manual are those in which the liquid and solid phases typically will not separate in normal handling and in which processes other than the introduction of solid particles and mixing are used to generate the grout. Mixtures of chemical and particulate grouts have the limitations of particulate grouts in terms of mixing, handling, and injection and so are best treated as particulate grouts (EM 1110-2-3506 and para 2-3*h*(2)).

b. Chemical grouting. Chemical grouting is the process of injecting a chemically reactive solution that behaves as a fluid but reacts after a predetermined time to form a solid, semisolid, or gel. Chemical grouting requires specially designed grouting equipment in that the reactive solution is often formed by proportioning the reacting liquids in an on-line continuous mixer. Typically, no allowance is made in chemical-grouting plants for particulate materials suspended in a liquid. Further, the materials used in the pumps and mixers are specifically selected to be nonreactive with the chemicals being mixed and pumped.

c. Background. Chemical grouts were developed in response to a need to develop strength and control water flow in geologic units where the pore sizes in the rock or soil units were too small to allow the introduction of conventional portland-cement suspensions. The first grouts used were two-stage grouts that depended on the reaction between solutions of metal salts and sodium silicate. The goal in this work was to bond the particles of soil or rock and to fill in the pore spaces to reduce fluid flow. The technology has expanded with the addition of organic polymer solutions and additives that can control the strength and setting characteristics of the injected liquid. Chemical grouting has become a major activity in remediation and repair work under and around damaged or deteriorated structures. Much of the technology for large-scale grouting of rock or soil can and has been adapted into equipment for repairing concrete structures such as pond liners, drains, or sewers.

1-6. Special Requirements for Chemical Grouts

a. General. In the selection of a grout for a particular application, certain chemical and mechanical properties should be evaluated. These include viscosity, durability, and strength. The following paragraphs serve to point out some of the more significant properties of grouts and grouted materials; however, these are not definitive guidelines for engineering design. In many

cases, it may be advisable to construct a small field-test section to determine the handling and behavioral characteristics of the grout.

b. Viscosity. Viscosity is the property of a fluid to resist flow or internally resist internal shear forces. A common unit of measure of viscosity is the centipoise (cP).* Viscosity is important in that it determines the ability of a grout to flow into and through the pore spaces in a soil. Thus, the flowability of the grout is also related to the hydraulic conductivity (permeability) of the soil. As a rule of thumb, for a soil having a hydraulic conductivity of 10^{-4} cm/sec, the grout viscosity should be less than 2 cP. Grouts having viscosities of 5 cP are applicable for soils with hydraulic conductivity greater than 10^{-3} cm/sec, and for a viscosity of 10 cP, the hydraulic conductivity should be above 10^{-2} cm/sec.

c. Gel time. Gel time or gelation time is the interval between initial mixing of the grout components and formation of the gel. Control of gel time is thus important with respect to pumpability. Gel time is a function of the components of the grout, namely, activator, inhibitor, and catalyst; varying the proportion of the components can change gel time. For some grouts, viscosity may be constant throughout the entire gel time or may change during this period. Thus, it is important to know variation with gel time because of problems related to pumping high-viscosity liquids. After gelation, a chemical grout continues to gain strength. The time interval until the desired properties are attained is called the cure time.

d. Sensitivity. Some grouts are sensitive to changes in temperature, dilution by groundwater, chemistry of groundwater including pH, and contact with undissolved solids that may be in the pumps or piping. Sensitivity to these factors may influence gel time.

e. Toxicity. Although most of the toxic grouts have been withdrawn from the market, personnel involved in grouting must maintain an awareness of the potential for certain materials to be or to become toxic or hazardous if not properly used. The basic approach should be to always follow the manufacturer's instructions in handling and disposing of such materials and to always follow safe practices in the field. Where large quantities of chemical grout are to be injected into the subsurface, it is prudent to consult the appropriate environmental regulatory agencies during planning.

f. Durability. Durability is the ability of the grout after pumping to withstand exposure to hostile conditions. These include repeated cycles of wetting and drying or freezing and thawing that may occur as a result of changes in climatic or environmental conditions. Certain chemicals in the soil or groundwater may also attack the grout and cause deterioration.

g. Strength. Among other applications, grouts are injected into soils, primarily granular materials, to add strength to the soil matrix. The unconfined compression test on grout-treated samples offers an index of the strength of the material and may suffice as a screening test for the effectiveness of the grout. In many situations, the grout may be placed and remain under the water table, in which case the strength of the saturated material may be lower than that of a dry specimen. In all cases, the strength of the grouted soil in situ must be sufficient to perform its intended function.

1-7. Advantages and Limitations of Chemical Grouts

a. The viscosities of chemical grouts can be very low, and except for fillers that may sometimes be used, chemical grouts contain no solid particles. For these reasons, chemical grouts can be injected into foundation materials containing voids that are too small to be penetrated by cementitious or other grouts containing suspended solid particles. Chemical grouts can therefore be used to control water movement in and to increase the strength of materials that could not otherwise be treated by grouting. Chemical grouts have been used principally in filling voids in fine granular materials; they have also been used effectively in sealing fine fissures in fractured rock or concrete. Chemical grouts have been frequently used for stabilizing or for increasing the load-bearing capacity of fine-grained materials in foundations and for the control of water in mine shafts, tunnels, trenches, and other excavations. Chemical grouts have also been used in conjunction with other void-filling materials for curtain grouting under dams constructed over permeable alluvium and for other treatments such as area grouting or joint grouting.

b. Chemical grouts suffer from the disadvantage that they are often more expensive than particulate grouts. Large voids are typically grouted with cementitious grout, and chemical grouting is done as needed. Chemical grouts are also restricted in some circumstances due to potentially toxic effects that have been observed with some of the unreacted grout components. Potential

* The SI unit of dynamic viscosity is the pascal.second; centipoise × 1.000 000*E-03 = pascal seconds (Pa.s)

groundwater pollution is a major consideration in the selection of the type of grouts to be used in many cases.

1-8. Proponent

The U.S. Army Corps of Engineers proponent for this manual is the Geotechnical and Materials Branch, Engineering Division, Directorate of Civil Works (CECW-EG). Any comments or questions regarding the content of this manual should be directed to the proponent at the following address:

Headquarters, U.S. Army Corps of Engineers
ATTN: CECW-EG
20 Massachusetts Ave., NW
Washington, DC 20314-1000

Chapter 2
Chemical Grout Materials

2-1. Types of Chemical Grout

Several kinds of chemical grouts are available, and each kind has characteristics that make it suitable for a variety of uses. The most common are sodium silicate, acrylate, lignin, urethane, and resin grouts. A general ranking of grouts and their properties is presented in Table 2-1. Typical applications of chemical grouts are presented in Table 2-2.

2-2. Factors Affecting Penetration

Penetration of grout in any medium is a function of the grout, the medium being injected, and the techniques used for grout injection. Typically, grouts that gel quickly have a limited range of treatment and require close spacing of injection holes and rapid injection rate. Low-shear-strength grouts are frequently useful in extending the range of treatment to times beyond initial gelation. Rapid times of setting are of use when a variety of different strata with different permeabilities are being treated and in situations where groundwater flow may displace the grout during injection (Bowen 1981). When gelling occurs before pumping is halted, the last-injected grout typically moves to the outside of the grouted mass, and both large and small openings are filled. Methods of injection are also of importance. Typically, grouts that are continually moving will gel less quickly, and penetration from continuous injection will be greater than that from the same volume of grout used in batch injection.

2-3. Sodium Silicate Systems

Sodium silicate grouts are the most popular grouts because of their safety and environmental compatibility. Sodium silicates have been developed into a variety of different grout systems. Almost all systems are based on reacting a silicate solution to form a colloid which polymerizes further to form a gel that binds soil or sediment particles together and fills voids.

a. Reactants. Sodium silicate solutions are alkaline. As this alkaline solution is neutralized, colloidal silica will aggregate to form a gel if the sodium silicate is present in concentrations above 1 or 2 percent (by volume). Three types of alkaline silicate grouts are recognized based on reactants used with silicate solutions (Yonekura and Kaga 1992):

(1) Acid reactant (phosphoric acid, sodium hydrogen sulfate, sodium phosphate, carbon dioxide solution).

(2) Alkaline earth and aluminum salts (calcium chloride, magnesium sulfate, magnesium chloride, aluminum sulfate).

(3) Organic compounds (glyoxal, acetic ester, ethylene carbonate formamide).

b. Processes. Sodium silicate and a reactant solution can be injected as separate solutions, or the sodium silicate can be premixed with the reactant to form a single solution that is injected.

(1) Two-solution process. The two-solution process is sometimes referred to as the Joosten two-shot technique (Bowen 1981, Karol 1990). In this approach, the sodium silicate solution is injected into the material to be grouted. The reactant solution, usually a solution of calcium chloride, is added as a second step. The two-solution approach is reported to produce the highest strength gain in injected soils but is considered to be the most expensive technique that is employed.

(a) The two-component technique can be made to form gel very rapidly. This near-instantaneous hardening can be very useful in shutting off water flow. An additional advantage is the permanent nature of the hardened grout. Bowen (1981) reports testing done on 20-year-old, grouted foundations that showed no apparent deterioration.

(b) The rapid hardening that occurs in the two-component technique restricts the volume of soil or sediment that can be treated from a single injection point. It typically is not possible to control the mixing of the silicate and reactant in the subsurface. Some unreacted grout components should be expected when the two-component system is employed.

(2) One-solution process.

(a) The one-solution process involves the injection of a mixture of sodium silicate and a reactant (or reactants) that will cause the silicate to form a gel. The separate solutions are prepared and mixed thoroughly. The one-solution process depends on the delay in the onset of gelation. This process offers the advantages of more uniform gel formation, improved control to gel distribution during injection, and reportedly strong grout.

Table 2-1
Ranking of Major Grout Properties

Type	Property					
	Penetration in Grouted Units	Durability	Ease of Application	Potential Toxicity	Flammability of Materials	Relative Costs
Portland-cement-based grouts	L[1]	H	M	L	N	L
Silicates	H	M	H	L	N	L
Acrylates	H	M	H	M	L	H
Lignins	H	M	H	H	L	H
Urethanes	M	H	M	H	H	H
Resins	L	H	M	H	M	H

[1] N = non-flammable; L = low; M = moderate; H = high.

Table 2-2
Ranking of Chemical Grouts by Application

Application	Type				
	Sodium Silicate	Acrylate	Lignin	Urethane	Resins
Adding strength	C[1]	C	C	R	R
Reducing water flow	C	C	C	U	R
Concrete repair	U	U	U	C	C
Sewer repair	U	U	U	C	C
Load transfer and support	U	U	U	C	U
Installation of anchors	R	R	R	U	C

[1] C = commonly used; U = used; R = rarely used.

(b) Reactants used in the one-solution process neutralize the alkalinity of sodium silicate in a way similar to the two-solution system, but the reactants are diluted and materials that react slowly (such as organic reagents) are used. Sodium bicarbonate and formamide are common reactants. One customary formulation involves mixing formamide, sodium aluminate, and sodium silicate. The formamide causes gelation, and sodium aluminate accelerates the gel formation after the initiation of gelation.

(c) The silicate solution concentration that may be used in grouting may vary from 10 to 70 percent by volume, depending on the material being grouted and the result desired. In systems using an amide as a reactant, the amide concentration may vary from less than 1 to greater than 20 percent by volume. Generally, however, the amide concentration ranges between 2 and 10 percent. The amide is the primary gel-producing reactant in the one-solution process. Concentration of the accelerators is determined by gel time desired. The viscosity of a silicate grout is dependent on the percentage of silicate in the grout; a high silicate concentration is therefore more viscous than a low silicate concentration and has less chance of entering small voids. The viscosity of a particular one-solution silicate is relatively low in concentrations of 60 percent or less. Viscosity versus concentration is tabulated below.

Sodium Silicate Concentration, percent	Viscosity (as Compared with Water) Factor
10	2.5
20	3.2
30	3.5-4.5
40	4.0-6.0
50	5.2-12
60	8.0-20
70	92

c. *Strength and permeability.* Sodium silicate grouts have been used to cut off water flowing through permeable foundations and to stabilize or strengthen foundations composed of granular materials and fractured rock. Granular materials that have been saturated with silicate grout develop quite low permeability if the gel is not allowed to dry out and shrink. Even though shrinkage may occur, a low degree of permeability is usually obtained. Treatment with sodium silicate grout will improve the strength and the load-bearing capacity of any groutable granular material coarser than the 75-μm sieve. Factors that influence strength are grain size, particle-size distribution, particle shape, absorption, the ability of the grout to adhere to the particle surfaces, moisture content, curing environment, and method of loading.

d. *Durability.* Grouts containing 35-percent or more silicate by volume are resistant to deterioration by freezing and thawing and by wetting and drying. Grouts containing less than 30-percent silicate by volume should be used only where the grouted material will be in continuous contact with water or for temporary stabilization.

e. *Silicate systems.* One widely used silicate-grout system contains sodium silicate as the gel-forming material, formamide as the reactant, and calcium chloride, sodium aluminate, or sodium bicarbonate in small quantities as an accelerator. Accelerators are used individually in special situations, not together; they are used to control gel time and to impart strength and permanence to the gel. The effect of the accelerator is important at temperatures below 37 °C and increases in importance as the temperature decreases. Excessive amounts of accelerators may result in undesirable flocculation or formation of local gelation, producing variations in both the gel and setting times that would tend to plug injection equipment or restrict penetration, resulting in poorly grouted area. The accelerator is usually dissolved in water to the desired concentration before the addition of other reactants, and the subsequent combination of this mixture with the silicate solution forms the liquid grout. The reactant and accelerator start the reaction simultaneously; however, their separate reaction rates are a function of temperature. At temperatures below 34 °C, the reaction rate of the accelerator is greater than the reaction rate of the reactant. The reverse is true above 37 °C. Generally, when high temperatures are experienced, an accelerator is not required.

(1) Silicate-chloride-amide system. A silicate-chloride-amide system can be used where there is a need for an increase in the bearing capacity of a foundation material. This system has been successfully used for solidification of materials below the water table. It is a permanent grout if not allowed to dry out, and with 35-percent or more silicate concentration by volume, the grout exhibits a high resistance to freezing and thawing.

(2) Silicate-aluminate-amide system. A silicate-aluminate-amide system has been used for strength improvement and water cutoff. Its behavior is similar to the silicate-chloride-amide system but is better for shutting off seepage or flow of water. The cost is slightly greater, and this system can be used in acidic soils.

(3) Silicate-bicarbonate-amide system. A silicate-bicarbonate-amide system can be used for semi-permanent grouting and for various surface applications when the stabilization requirement is for relatively short periods of time.

(4) Silicate salt of a weak acid (Malmberg system).

(a) The Malmberg system is based on the production of a silicic acid gel by the mixture of a solution of sodium silicate with a solution of the salt of a weak acid. This system differs from other similar two-solution systems since they are based on a precipitate and differs from acid reaction systems by maintaining an alkaline pH. This system has a delayed silicic acid gel formation.

(b) Reactants used in this system include acid, alkali, or ammonium salts of weak acids such as sulfurous, boric, carbonic, and oxalic acid. Specific salts include sodium bisulfite, sodium tetraborate, sodium bicarbonate, potassium hydrogen oxalate, potassium tetraoxalate, and sodium aluminate. These salts will yield differences in performance. For optimum effect, the salt should be chosen on a basis of all of the factors of application. All of these salts will perform adequately for many strengthening or water-shutoff applications.

(c) The proportioning of the sodium silicate to the total volume of grout can range from 10 to 75 percent by volume with most work being done in the 20- to 50-percent range. The liquid silicate may be used as a diluted stock solution or mixed with water during the reaction with the acid-salt stock solution. There are a variety of sodium silicate products on the market, and it is important to use the correct concentration.

(d) This system has a small corrosive effect on light metals such as aluminum; however, the effect is not strong enough to warrant anything other than conventional equipment in mixing and pumping.

(e) For fast gel times, a two-pump proportioning system is desirable, as with some other systems; however, for slow gel times, batch mixing can be employed. Compressed-air-bubble mixing or violent mixing that introduces air should not be used because of the reaction between the solutions and carbon dioxide.

(f) The gel time can be controlled with this system, as with other systems, by varying solution concentrations. Increasing the sodium silicate concentration retards gel time; increasing the acid-salt concentration decreases gel time; increasing temperature decreases gel time, and vice versa. Gel times are also influenced by the chemistry of the formation being treated. Acid soils, or soils containing gypsum, frequently accelerate gel time, whereas alkaline soils may decrease or even prevent gelation.

(g) Sands stabilized with the Malmberg system have shown a permeability in the range of 10^{-8} cm/sec, and when allowed to dry out, the permeability often increases to 10^{-5} cm/sec with the sample still having good strength characteristics. This means that this system is useful for water shutoff below the water table or where there is sufficient moisture to continually replace water lost due to evaporation. This system should not be used for water shutoff in rock or other open fissures due to a large degree of syneresis.

(h) This system is permanent above the water table, if some unreacted sodium silicate is present, and in most applications below the water table. Limited field experience has shown this system to perform satisfactorily under such conditions as thin surface applications in the Nevada desert.

(i) Fine sands with up to 10 percent passing a 75-µm sieve can be penetrated by a grout containing up to 50 percent, by volume, of sodium silicate if a surfactant is used. On one project, a 25-percent, by volume, sodium silicate grout was successfully injected in a sand with 22 percent passing a 75-µm sieve.

(j) Lubricity and viscosity are two important factors in the penetration characteristics of this system. For example, when mixed with the proper surfactant, a 10-cP Malmberg-system grout is reported to penetrate materials not penetrated by a 3-cP system. For a grout with a given lubricity, the less viscous will penetrate better than the more viscous.

f. Penetration. A 30-percent silicate solution has a lower practical limit of penetrability for material passing a 106-µm sieve with not more than 50 percent passing a 150-µm sieve or not more than 10 percent passing a 75-µm sieve. Gel time can be controlled from minutes to hours at temperatures ranging from freezing to 21 °C. The stability of the grout is excellent below the frost line and the water table, and poor when subjected to cycles of wetting and drying or freezing and thawing. Grout penetration is influenced by the following factors: depth of overburden, allowable pressure, void ratio and permeability of material being grouted, distribution of particle sizes, etc. The most fluid silicate grout (i.e., the silicate grout with the lowest silicate concentration) has the ability to penetrate materials coarser than the 75-µm

sieve (para 2-3*g*(5)). One of the most viscous (i.e., 70-percent silicate concentration) silicate grouts commonly used will penetrate materials coarser than the 300-µm sieve or not more than 25 percent passing the 106-µm sieve or not more than 25 percent passing the 75-µm sieve.

g. Physical properties and factors affecting gel time.

(1) Figure 2-1 shows the rate of strength development for various concentrations of sodium silicate grout injected into sand of unknown grading in which a 30-percent solution of calcium chloride was used as the reactant. The tests were conducted on laboratory-prepared specimens, and a two-solution system was employed.

(2) Figure 2-2 is a plot of gel time versus temperature for a 20-percent silicate concentration in the silicate-chloride-amide system, and Figure 2-3 is a plot of gel time versus accelerator concentration for a 20-percent silicate concentration in the silicate-aluminate-amide system. Both Figures 2-2 and 2-3 are for one concentration of silicate.

(3) The following factors affect the gel times of the one-solution silicate grout:

(a) An increase in silicate concentration increases the gel time if other ingredient concentrations are held constant.

(b) An increase in the reactant concentration decreases the gel time.

(c) An increase in the concentration of the accelerator, within limits (para 2-3*e*), decreases the gel time.

(d) Gel times are decreased with an increase in temperature. Up to 48 °C, no special precautions are necessary.

(e) The pH of the material to be grouted has little effect except where large amounts of acid are present. When acid is present, silicate grout containing aluminate should be used (para 2-3*e*(2)).

(f) The presence of soluble salts such as chlorides, sulfates, and phosphates in the medium to be grouted has an accelerating effect on the gel time depending upon their concentration.

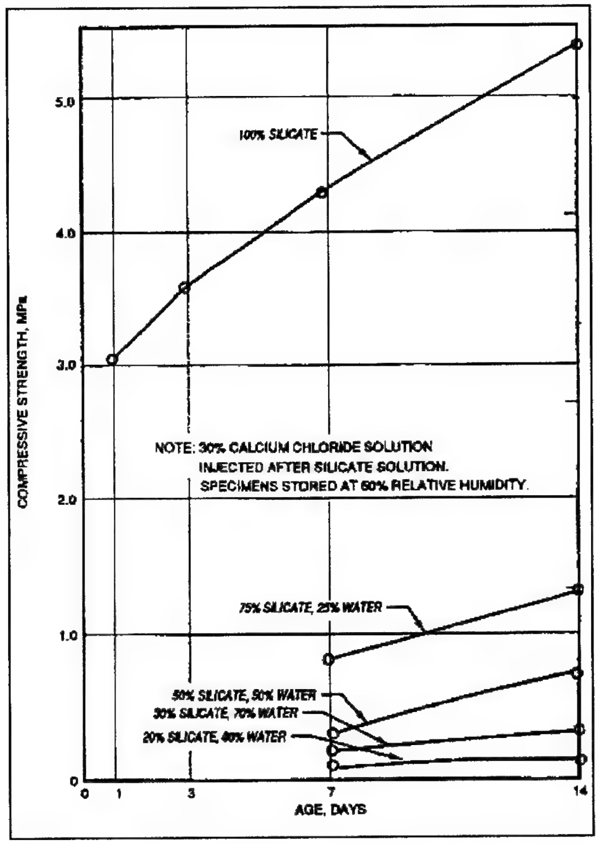

Figure 2-1. Effect of dilution of silicate grout upon compressive strength of solidified sand (after Polivka, Witte, and Gnaedinger 1957)

(g) Impurities or dissolved salts in some waters may have an effect on gel time; hence, the gel time should be determined using water from the source that is to be used in the final product.

(h) Direct sunlight has no effect on gel time; however, see para 2-3*g*(3)(d).

(i) Freezing has little effect on silicate-grout ingredients; however, freezing must be avoided during placement.

(j) Some filler materials such as bentonites and clays have little effect on gel time. However, if moderate to high concentrations of fillers are used, the temperature will vary, which would change the gel time. If reactive materials are used (such as portland cement (see

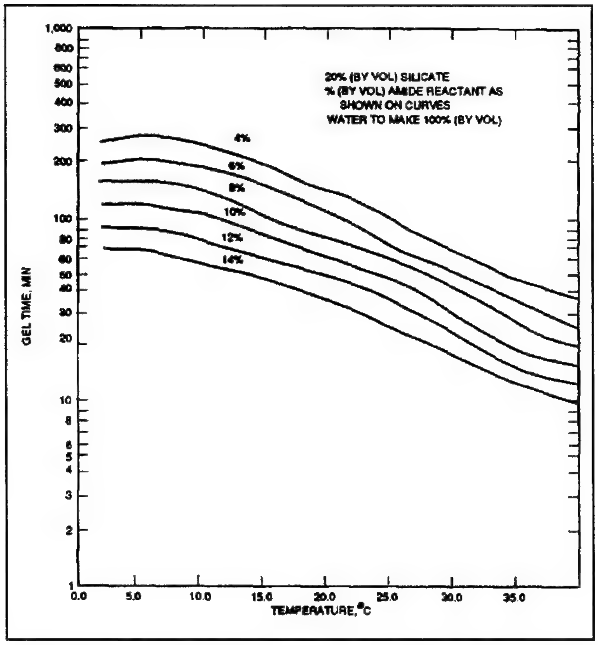

Figure 2-2. Gel time versus temperature, silicate-chloride-amide system (adapted from Raymond International, Inc. 1957)

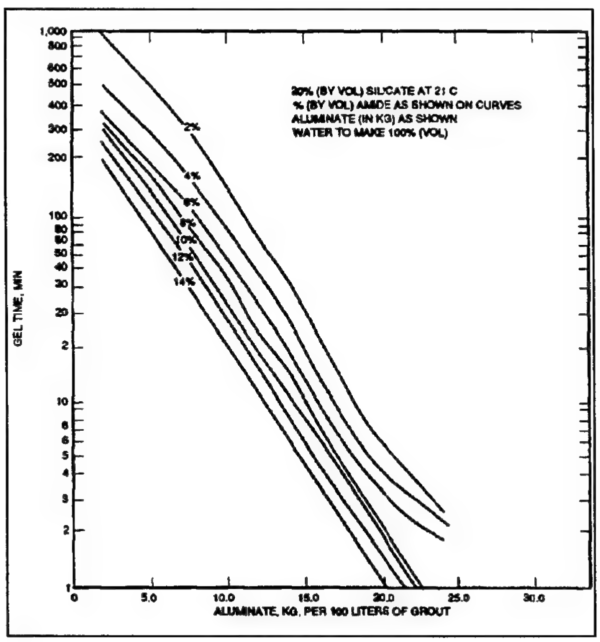

Figure 2-3. Gel time versus accelerator concentration, silicate-aluminate-amide system (adapted from Raymond International, Inc. 1957)

para 2-3*h*)), their effect on gel time and on the final product should be checked.

(4) Sodium silicate is noncorrosive to metals. Reactants such as amide and their water solutions will attack copper and brass, but they are noncorrosive to aluminum and stainless steel. The chloride solutions are not corrosive to iron and steel in the sense that acids are; however, if steel in a chloride solution is exposed to air, rusting will occur at the junction of the liquid and air. Bicarbonate is noncorrosive.

(5) Generally, the strength and load-bearing capacity of any groutable granular material coarser than 75-µm sieve can be improved when treated with a silicate grout. Table 2-3 gives some general guidelines as to what unconfined compressive strengths can be expected from materials grouted with sodium silicate.

(6) The strength of a grouted granular material is primarily a function of grout concentration and relative density of the formation. In grouted loose material,

Table 2-3
Unconfined Compressive Strengths of Various Materials Treated with Silicate Grout

Material	Compressive Strength, kPa, of Material After Grouting
Very loose granular material saturated with a silicate grout, cured dry	4,000-7,000
Very loose granular materials saturated with a silicate grout, cured at 80-100% relative humidity	2,800-3,500
Very loose granular materials saturated with a silicate grout, cured underwater	700-2,800
Average field conditions with one injection (incomplete saturation)	700-2,800
Compact, medium-grain granular materials saturated with a silicate grout, wet subsurface	200-4,000

strength is governed by the gel and only slightly modified by the material itself. The angle of internal friction can be increased from that of the unstablized state. For dense, compacted grouted material, strength is governed primarily by the material.

(7) Tests indicate that 40-percent and stronger silicate grouts have high durability and are permanent, with the exception of the grouts containing bicarbonates. Tests and observations have indicated silicate grouts to be permanent under freeze-thaw conditions, dimensionally stable to temperature, and resistant to acidity, alkalinity, salinity, bacteria, and fungi. Granular materials or rocks that are completely saturated with grout are essentially impermeable if the gel is not allowed to dry out and shrink.

h. Portland cement-sodium silicate compatibility.

(1) Portland cement can be used as a filler in silicate grouts but acts as an accelerator. Extremely short gel times have been experienced when portland cement was used, making this system very useful for cutoff of flowing water or water under pressure. Strong bonding properties to the in situ materials have been reported when silicates were combined with portland cement. This system has been used in grouting below a water table and produces a high-strength, permanent grout if not allowed to dry out. Gel or set times in the range of 10 to approximately 600 sec with strengths as high as 7,000 kPa have been reported, with these short gel times being obtained by increasing the amount of cement. Finely ground portland cements are typically most useful with sodium silicates.

(2) Sodium silicate grout can be injected more easily than a silicate-portland-cement grout, which, in turn, can be injected more easily than portland-cement mixtures. Silicate-portland-cement grout can be injected more easily than portland-cement mixtures apparently because the cement particles are lubricated by the silicate.

2-4. Acrylate Grouts

Acrylates were introduced as less toxic alternatives to the toxic acrylamide compounds that are no longer available as grout. Acrylate grout is a gel formed by the polymerization of acrylates. The gelling reaction is catalyzed by the addition of triethanolamine and ammonium or sodium persulfate to a metal acrylate (usually magnesium acrylate). Methylene-bis-acrylamide is used as a cross-linking agent. Potassium ferricyanide is used as an inhibitor if long times of setting are required.

a. Principal uses. Acrylates have replaced acrylamide as the usual grout for forming water stops around sewer systems. Acrylate is typically not used in areas where it is subject to wetting and drying or freezing and thawing.

b. Strength and permeation. Acrylates typically form soft gels. Standard sand samples grouted with acrylates can obtain strengths as high as 1.5 MPa. Acrylate grouts can be prepared with viscosities as low as 1 cP. The low viscosity and ability to develop long gel times (up to 120 min) make acrylate grouts useful in fine sediments.

c. Modified acrylate grouts. Specialized acrylate grouts have been developed by using acrylate grout in a two-part injection technique with each injected solution a monomer (silicate or acrylate, for example) and the catalyst for the other monomer. This type of special application grout is restricted to use at temperatures between 5 and 30 °C.

2-5. Urethanes

Urethane grouts are available in several different forms, but all depend on reactions involving the isocyanates cross-linking to form a rubbery polymer. One-part polyurethane grouts are prepolymers formed by partly reacting the isocyanate with a cross-linking compound producing a prepolymer with unreacted isocyanate groups. The one-part grouts react with water to complete polymerization. The grouts will typically gel or foam depending on the amount of water available. Viscosities range from 50 to 100 cP. The two-component grouts employ a direct reaction between an isocyanate liquid and a polyol and produce a hard or flexible foam depending on the formulation. Viscosities range from 100 to 1,000 cP. Factors that affect the application of urethanes include the following:

a. Toxicity. Isocyanates typically are toxic to varying degrees depending on the exact formulation. The solvents used to dilute and control the viscosity of the urethane prepolymers are also potential groundwater pollutants. There are additional safety problems related to combustion products produced if the grout is exposed to flame. Some grouts are highly flammable before and after setting.

b. Adaptability. Urethane grouts have provided very versatile materials. They can be injected directly into flowing water as a water stop and can be used for seal openings as small as 0.01 mm. Rigid foams have found

applications in distributing loads in underground structures.

2-6. Lignins

When combined with a oxidizer such as sodium dichromate, lignin, a by-product of the sulfite process of making paper, forms an insoluble gel after a short time. Viscosities of various lignin solutions can be obtained over a range that makes the lignins capable of being injected into voids formed by fine sands and possibly coarse silts. Lignins are generally not acceptable if chromium compounds are used due to the toxicity of chromium.

a. Types of lignin-based grouts.

(1) Lignin-based grouts are injected as a one-solution single-component system, the reactant or reactants being premixed in the lignin-based material. Gel times with the precatalyzed lignosulfonate system are easily adjusted by changing the quantity of water. This precatalyzed lignosulfonate is reported to be a dried form of chrome lignin.

(2) Two-component systems of lignosulfonates are also commercially available. The reactants of this system are mixed separately as with a proportioning system, and the total chemical grout is not formed until immediately prior to injection. Advantages of this system are closer control of gel time and a wider range of gel times coupled with elimination of the risk of premature gelling.

(3) The materials used in lignin grouts are rapidly soluble in water, although mechanical agitation is recommended. The lignin gel in normal grout concentrations is irreversible, has a slightly rubbery consistency, and has a low permeability to water. Short-term observations (less than 2 years) show that for grouted materials protected against drying out or freezing, the grout will not deteriorate.

b. Uses. Lignin grout is intended primarily for use in fine granular material for decreasing the flow of water within the material or for increasing its load-bearing capacity. These grouts have also been used effectively in sealing fine fissures in fractured rock or concrete. Their use in soils containing an appreciable amount of material finer than the 75-μm sieve generally is unsatisfactory and is not recommended because material this fine will not allow satisfactory penetration. However, lignin grout of low viscosity injected at moderately high pressures may be effective in fine materials.

c. Reactants.

(1) Various reactants used with lignin-based grouts include sodium bichromate, potassium bichromate, ferric chloride, sulfuric acid, aluminum sulfate (alum), aluminum chloride, ammonium persulfate, and copper sulfate. The bichromates have been the most widely used and apparently are the most satisfactory, but now are considered a potential grout-water pollutant.

(2) Ammonium persulfate has also been used as a reactant in the lignin-grout system, but the ultimate strength is approximately 40 percent of that of a similar grout mixture in which sodium bichromate is used as a reactant.

2-7. Resins

Resin grouts consist essentially of solutions of resin-forming chemicals that combine to form a hard resin upon adding a catalyst or hardener. Some resin grouts are water based or are solutions with water. Injection is by the one-solution process. The principal resins used as grouts are epoxy and polyester resins. The terms *epoxy* and *polyester resins* apply to numerous resin compounds having some similarity but different properties. Various types of each are available, and the properties of each type can be varied by changing the components. Resins can be formulated to have a low viscosity; however, the viscosities are generally higher than those of other chemical grouts. A large amount of heat is generally given off by resins during curing. They retain their initial viscosity throughout the greater part of their fluid life and pass through a gel stage just before complete hardening. The time from mixing to gel stage to hardened stage can be adjusted by varying the amount of the hardening reactant, by adding or deleting filler material, and by controlling the temperature, especially the initial temperature.

a. Epoxies. Epoxy grouts are generally supplied as two components. Each component is an organic chemical.

(1) Normally, the two components are a resin base and a catalyst or hardener; a flexibilizer is sometimes incorporated in one of the components to increase the ability of the hardened grout to accommodate movement. Tensile strengths generally range in excess of 28 MPa in both filled and unfilled system. A filled system is one in which another ingredient, generally material such as sand, has been added. An unfilled system refers to the original mixture of components. Elongation may be as

much as 15 percent. Flexural strength in both filled and unfilled systems is generally in excess of 40 MPa with considerably higher strengths reported in some instances with filled systems. Compressive strengths greater than 70 MPa are attainable and may reach 270 MPa in a filled system. Water adsorption is approximately 0.2 percent or less and shrinkage, by volume, is 0.01 percent and lower.

(2) Epoxy resins, in general, also exhibit the following characteristics: resistance to acids, alkalies, and organic chemicals; a cure without volatile by-products (therefore, no bubbles or voids are formed); ability to cure without the application of external heat; acceptance of various thixotropic or thickening agents such as special silicas, bentonite, mica, and short fibers such as asbestos or chopped glass fiber; and capability of being used in combination with various fillers to yield desired properties both in hardened and unhardened state.

(3) Examples of epoxy fillers are aluminum silicate, barium sulfate, calcium carbonate, calcium sulfate, and kaolin clay, which act as extenders; graphite, which aids in lubricating the mixture; and lead for radiation shielding. These fillers are generally added to reduce the resin content and in most instances reduce the cost. Fillers reduce heat evolution, decrease curing shrinkage, reduce thermal coefficient of expansion, and increase viscosity. The tensile strength, elongation, and compressive strength are adversely affected by the addition of granular fillers.

(4) In general, epoxy resins are easier to use than polyesters, exhibit less shrinkage, develop a tighter bond, and are tougher and stronger than polyesters. Epoxies are thermosetting resins; hence, once they have hardened, they will not again liquefy even when heated, although they may soften.

(5) Epoxy resin grouts have been used for grouting of cracked concrete to effect structural repairs; more recently, for grouting fractured rock to give it strength; and in rock bolting.

b. Other resins.

(1) Aqueous solutions of resin-forming chemicals. A commercially available resinous grouting material has been investigated for possible use in grouting in sandstone to reduce water flow. The resin solution has a viscosity of 13 times that of water and is hardsetting. Two aqueous solutions of resin-forming chemicals compounded with accelerators and retarders are employed in this grout. The two resin-forming materials solidify upon addition of the catalyst to form a hard plastic. Investigations have shown that the time of setting of this grout can be accelerated by chemicals in the sandstone. Water-flow pressure tests before and after grouting have shown that a reduction in flow through test specimens was obtained.

(2) Water-based resin. A water-based-resin grouting material having an initial viscosity of approximately 10 cP is commercially available. This grout has an affinity for siliceous surfaces and attains a hard set. Tests on a clean, medium-fine sand grouted with this resin have shown compressive strengths of approximately 8 MPa. This grout is used in grouting granular materials, presumably to reduce water flow. Sandy soils containing as much as 15 percent in the coarse silt range (0.04 mm) can be treated with this material. In calcareous materials, this grout will not set properly. The gelled grout is not affected by chemicals generally present in underground water. The neat gel has a compressive strength of 5.5 MPa in 3 hr; has a low permeability to water, oil, or gas; and is stable under nondehydrating conditions; however, when water is lost, shrinkage will occur with an accompanying strength loss. Medium-fine sands (0.5 to 0.1 mm) injected with this material have compressive strengths in the 10.3-MPa range. In laboratory studies, sands treated with this material showed no deterioration under wet conditions at the end of 1 year.

(3) Concentrated resin. Concentrated resins are marketed and are intended for use where strength and waterproofing are necessary. These resins are used in sand, gravel, and fractured and fissured rock. Presumably, they could also be used in fractured concrete. Laboratory tests with both a 50- and an 80-percent concentration (50:50 and 80:20, by volume, resin to water) of resin indicated that fractures as small as 0.05 mm could be grouted. These tests were performed by injecting grout between two pieces of metal separated by appropriate size shims. Approximately 7 MPa was required to inject both concentrations into the 0.05-mm spacing. Tests on spacings smaller than 0.05 mm were not performed. The viscosity of the concentrated resin ranges between 10 and 20 cP for normal concentrations used and temperatures encountered in the field. The base material is liquid diluted with water and reacted by a sodium bisulfate solution. Gel times are controllable and with normal concentrations (50:50, by volume, resin to water) reach a firm solidification set within 24 hr. Strengths of stabilized sand after curing have reached 3 to 35 MPa. Strength is a function of amount of mixing water used and decreases with an increase of water. If strength is not a consideration, the base material may be

diluted with up to twice its volume of water to provide temporary water control. If used in this manner, viscosities will be lower and gel times longer. Soils and rock masses can attain permeabilities on the order of 1×10^{-7} cm/sec. Gel time varies as a function of solution temperature and reactant concentration. Stainless steel should be used throughout the reactant side if the proportioning system of pumping is employed.

2-8. Other Grouts

The five groups of chemical grouts discussed previously are not the only chemical grouts that have been or can be used. Some of the other chemical grouts include a cationic organic-emulsion using diesel oil as a carrier, a resorcinol-formaldehyde, an epoxy-bitumen system, a urea-formaldehyde, and a polyphenolic polymer system. Most of these grouts are no longer used due to toxicity. A variety of special application grouts have also been developed for structural repair and for installation of anchors. These include thermo-setting grouts such as molten sulfur and molten lead. Additionally, special epoxies and acrylates have been developed as bolt anchoring and concrete patching kits.

Chapter 3
Grouting Equipment and Methods

3-1. Grout-Mixing Equipment

a. Mixing and blending tanks. Mixing and blending tanks (Figure 3-1) for chemical-grouting operations should be constructed of materials that are not reactive with the particular chemical grout or with individual component solutions. Tanks can be of aluminum, stainless steel, plastic, or plastic-coated as appropriate. Generally, the capacity of the tanks need not be large. The number and configuration of the tanks depend on the mixing and injection system used.

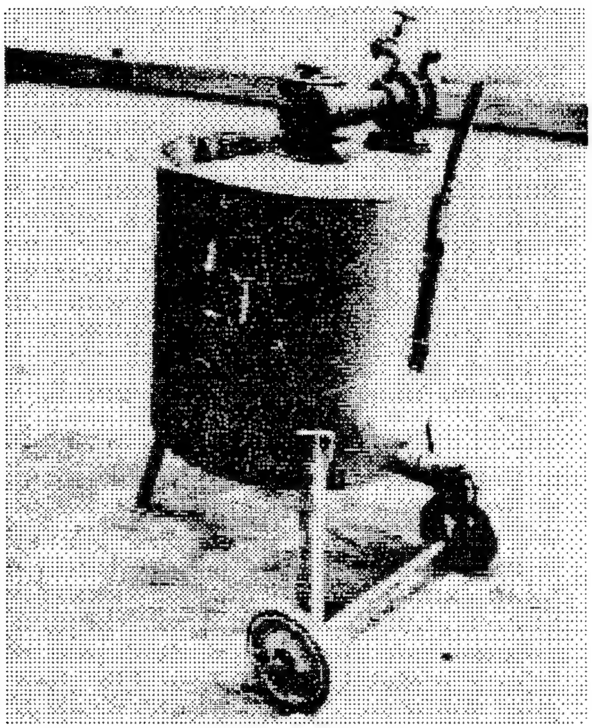

Figure 3-1. Mixing tank with mechanical mixing action

b. Batch system. The simplest grout-mixing system is the batch system commonly used in conventional portland-cement grouting. In the batch system, all of the components including the catalyst are mixed together at the same time, generally in a single tank. While this method allows for simplicity, the disadvantage is that pumping time is limited to the gel time; if the grout sets before pumping is completed, pumps, pipes, and flow channels may become clogged.

c. Two-tank system. A more advantageous method involves the use of two tanks with one tank containing the catalyst and the other tank containing all of the other components (Figure 3-2). In this method, material from both tanks are delivered into a common pump where the catalysis is initiated. The grout is then fed through a hose to the injection point. Pumping time is independent of gel time, which cannot be initiated until all components are mixed.

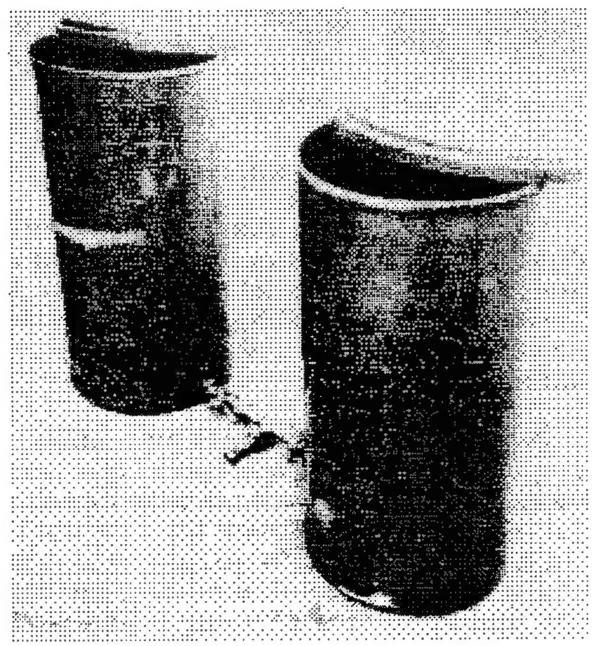

Figure 3-2. Dual mixing-tank arrangement

d. Equal-volume method. A variation of the two-tank procedure is the equal-volume method (Figure 3-3). In this method, identical pumps are attached to each tank and are operated from a common drive. The components in each tank are mixed at twice the design concentration. The equal-volume system offers the advantage that mistakes in setting metering pumps cannot occur and the concentration of the two grout components can be tailored by the manufacturer.

3-2. Pumping Equipment

Pumps that could be used satisfactorily for chemical grouting include positive-displacement and piston pumps.

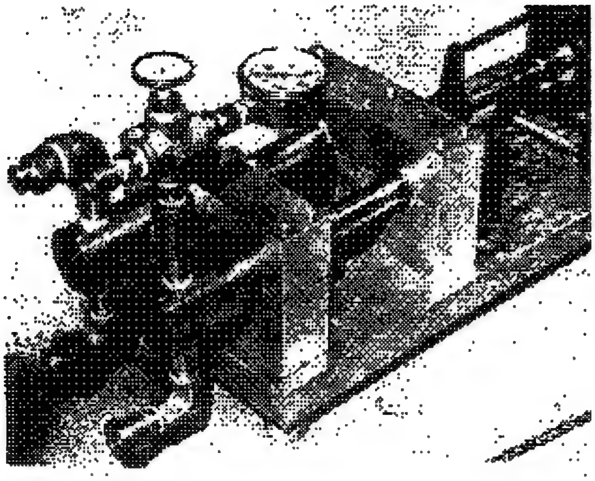

Figure 3-3. Equal-volume system

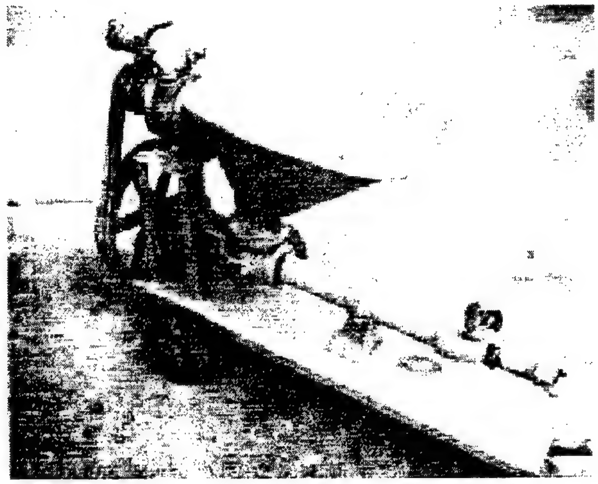

Figure 3-4. Positive-displacement screw pump

a. Positive-displacement pumps.

(1) Probably the most commonly used positive-displacement pump is the screw, in which a stainless-steel rotor turns within a flexible erosion- or chemical-resistant stator, forming voids that carry the material toward the discharge end of the pump at a constant rate (Figure 3-4).

(2) A pumping arrangement which can be adapted to chemical grout (and which can be operated by one man) consists of dual positive-displacement pumps mounted on a single frame. The pumps operate from a single power unit; however, the gear ratio of one pump can be varied, whereas the other pump has an unvarying gear ratio. This arrangement enables the operator to make a quick change in the proportion of reactant and the gel time by changing the gear ratio of the pump. The pump with the variable gear ratio is generally used to pump the ingredient of the grout that initiates reaction.

(3) Positive-displacement pumps produce less pulsation and thus are able to maintain a more uniform pressure, especially at low pressures, than piston pumps.

b. Piston pumps.

(1) In the event piston pumps are used, there are some advantages of specific varieties that should be recognized. Better volume and pressure controls in the lower ranges can be obtained using simplex pumps. The simplex pump (Figure 3-5) operates with the one piston activating four fluid valves and produces a flow that pulsates more than that of the duplex. The duplex operates with two pistons and eight fluid valves. Because of their smaller size, simplexes are more suitable for use in tunnels and shafts where space is a problem. Piston pumps typically can develop higher pressures than the positive-displacement pumps such as the progressive cavity pumps. Piston pumps may require more lubrication and attention to wear because of the metal-to-metal contact and close tolerances built into these units. Piston pumps developed for point and other high-viscosity liquids have been adapted for grouts. These designs are often useful because of their ease of disassembly for cleaning.

(2) There are no limitations as to type, size, or style of pump to be used in chemical-grouting operations; however, a number of features and characteristics should be considered in the selection of a pump. These include pumping rate; capacity or size; mass; maximum and minimum pressure requirements; limitations, mobility, maintenance, and availability of repair parts; and resistance to attack by the ingredients of the chemical grouts. Ease of assembly and disassembly during operation is very important. The chemical action in some chemical grouts may be accelerated or possibly retarded by the reaction of some of the grout solutions with parts of the pump. The possibility of a chemical reaction between the grout and metals and other materials in the pumps and its effect on the grout must be considered in choosing any particular pump. Because of differences in the metals used in piston pumps, it is prudent to consult the pump supplier when a grout job is being planned.

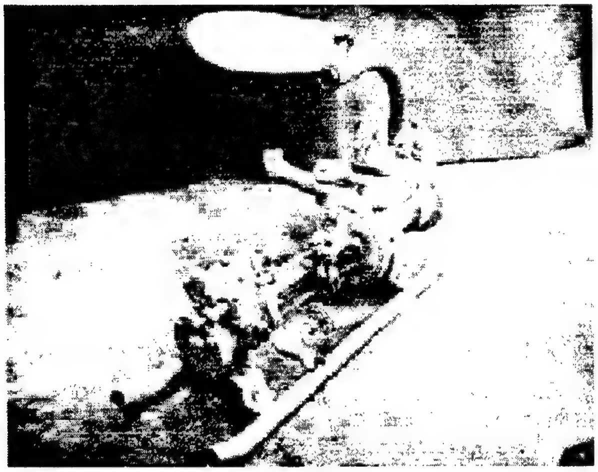

Figure 3-5. Simplex pump

Often valves and fittings are more easily corroded than the pistons and cylinders. Details in pump construction are important.

(3) Pressures up to 70 MPa and higher and pumping volumes ranging from a fraction of a liter to hundreds of liters per minute can be obtained with commercially available pumps. Pumps can be obtained that will operate on air, gasoline, or electricity. Reversible air motors are helpful for unclogging plugged lines, especially when fillers are used in the grout. Air motors are also durable, are simple to operate, and have a low silhouette. Air motors should be considered for use in shafts and tunnels from the standpoint of safety. Generally, they are smaller than gasoline or electric motors capable of an equal horsepower output.

c. Accessory equipment. For the most part, accessory equipment for chemical-grouting operations such as hoses, valves, fittings, piping, blowoff relief valves, headers, and standard drill rod can be the same as that for portland-cement-grouting operations. Possible exceptions include connections between pumps, mixing and blending tanks, and injection lines or pipes. These connections should be of the quick-release type because of the rapid gel time that can be obtained with some chemical grouts. In some cases, it can become necessary to disconnect and disassemble equipment for cleaning. The material of which the pump and accessory equipment is constructed may have an effect on gel time. For this reason, each grout should be checked against the entire injection system prior to use.

3-3. Pumping Systems

Pumping systems that can be used to satisfactorily inject chemical grout are listed below:

a. Variable-volume pump system or proportioning system.

(1) This system (Figure 3-6) is used to vary gel times, pumping rates, and pumping pressures and allows one man to control all of these factors rapidly by mechanical means. The need for solution composition or concentration adjustment is eliminated during an application.

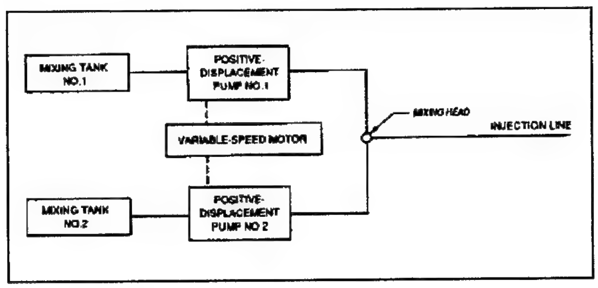

Figure 3-6. Variable-volume pump system or proportioning system

(2) By the use of two variable-volume motors (Figure 3-7), the gel time can be changed without appreciably changing the basic chemical concentration of the final mixture, and total volume pumped can be changed without changing the gel time. It may be desirable to add a third pump, or a third pump and tank, to a metering system. Figure 3-7 Shows an early version of this type of unit.

b. Two-tank gravity-feed system.

(1) This system (Figure 3-8) normally permits only one predetermined gel time. Any attempt to change gel time requires that carefully weighed amounts of catalysts and accelerators are added to the proper tanks.

(2) The mixing tanks should be of identical size and volume, and the surface of the solutions should be at the same height in the respective tanks. Equal volumes of solutions are drawn from the two mixing tanks into the

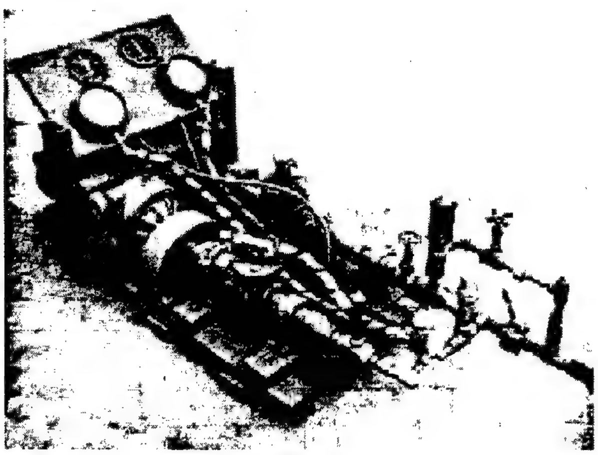

Figure 3-7. Variable-volume pump arrangement

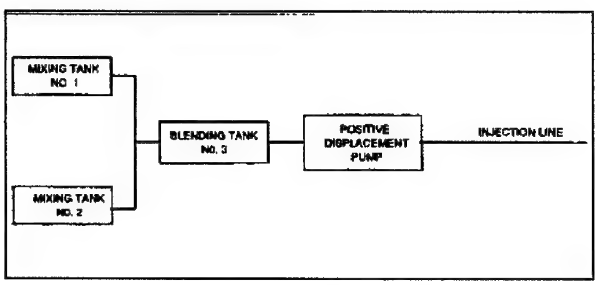

Figure 3-8. Two-tank gravity-feed system

blending tank, where they are mixed and fed to the pump. This system can be modified by using two pumps of equal capacity driven by the same motor (Figure 3-9).

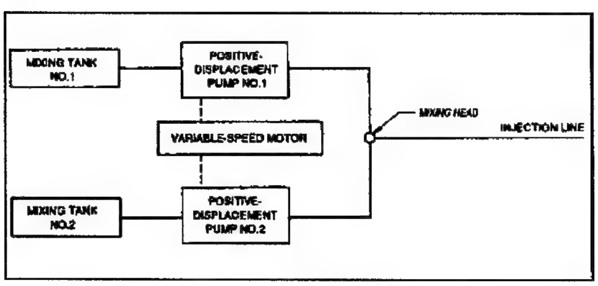

Figure 3-9. Two-tank gravity-feed system (variation)

This will eliminate the use of a blending tank. Short gel times are possible with this system; however, a disadvantage of the system is that experience is needed to obtain accurate changes in gel time while dispensing from premixed solutions.

c. Batch system. In this system, all materials are mixed in one tank (Figure 3-10). This system has three basic limitations:

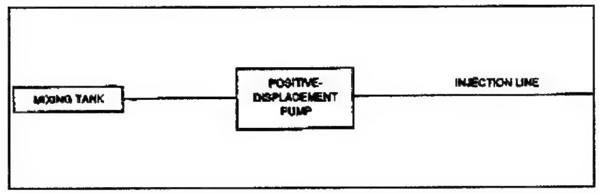

Figure 3-10. Batch system

(1) The entire batch must be placed during the established gel time; however, because pumping rates often decrease as injection continues, this is not always possible, and the danger of gelation in the equipment is always present.

(2) Difficulty is experienced in varying the gel times during pumping.

(3) Very short gel times cannot be used unless only small batches are used.

d. Gravity-feed system. In some instances, it may be desirable to pump or pour the grout to its desired location and allow the grout to seek its own level. The most economical means of doing this would be to discharge directly from mixing units; however, a pump is required if the area to be grouted is some distance from the mixing setup and the mixing setup cannot be moved.

3-4. Injection Methods

a. General. The ultimate goal of grouting is to place a specified amount of grout at some predetermined location. Grout placement downhole can be accomplished by several means. The simplest grouting situation is to pump or pour the grout directly onto surface or into an open hole or fracture. The simplest downhole method using pressure for placement involves the use of one packer to prevent the grout from coming back up the hole while it is being pumped.

b. Packers. Selective downhole grouting, for use in a competent hole, can be accomplished by placing two packers, one above and one below the area to be treated,

and then injecting the grout. Another selective grout placement method is by use of "tubes à manchettes." This method entails using a tube with a smooth interior that is perforated at intervals and sealed into the grout hole. The perforations are covered by rubber sleeves, "manchettes," which act as one-way valves. Selective grout placement is obtained by a double-packer arrangement that straddles the perforations.

c. Other methods. Other methods include driving a slotted or perforated pipe into a formation; grouting, or driving, an open-end pipe to a desired elevation; and then grouting. The pipe can be kept open by temporarily plugging the open end with a rivet or bolt during driving. When the desired elevation is reached, the pipe is raised several inches to allow the rivet or bolt to work free from the open end when pressure is applied by grouting. The pipe may also be unplugged by placing a smaller rod inside the injection pipe to the total hole depth and slightly beyond. The rod is withdrawn from the pipe, and grout is injected. Another method, which can be used with the two-solution process, is to drive a perforated pipe a certain distance and inject the grout solution. This process is continued until the total depth is reached; then, grout solutions of the remaining chemicals are injected to complete the grout hardening reactions as the pipe is extracted.

Chapter 4
Planning

4-1. Regulatory Requirements

In the past 10 years, a number of chemical grouts have been removed from the market because of toxicity problems. For example, use of acrylamides and similar material was banned in Japan a number of years ago after several cases of contamination of drinking water wells were reported. Precautions must be taken, therefore, when there is the possibility of chemical grouts coming in contact with wells or groundwater or where the presence of a chemical grout could cause problems at some later time. Even seemingly innocuous materials can have harmful results, such as affecting the pH of groundwater. It is essential that before work is begun, all possible harmful effects of chemical grouting be ascertained. In addition, all applicable laws, regulations, and restrictions must be reviewed thoroughly. Not only should Federal statutes be reviewed but also those of states, cities, and other government entities.

4-2. Preliminary Planning

The planning of a chemical-grouting program consists of procedures similar to those for any other grouting operation. Planning involves establishing the purpose for grouting, obtaining a description of the job, determining the field conditions, performing the necessary field sampling and testing, conducting a laboratory program to reveal the characteristics of the material to be grouted, and determining the suitability of the various chemical grouts to satisfactorily complete the job. After these items are completed, personnel, field procedures, and equipment required can be established.

a. Background information. Certain background information is needed to determine the feasibility of chemical grouting. This includes:

(1) A description of the problem that is being addressed. This includes a quantitative assessment of the degree of strength required or the need to reduce water flow.

(2) Results of drilling and sampling in the area to be treated, delineation in terms of geologic strata and their thicknesses, and extent with respect to surface locations and varying water-table elevation to include determination of groundwater elevations and gradients. Drilling and sampling are performed to determine the location and nature of the zones that might require additional grouting and to permit a preliminary estimate of the type or types and quantities of grout required. The information desired is determined by laboratory or field tests on samples judged to be representative of the zone from which they were obtained.

(3) Data on characteristics of the medium to be grouted, such as particle size and permeability (Table 4-1).

(4) Chemical composition of groundwater and of the medium to be grouted.

Table 4-1
Approximate Soil Properties

Soils[1]	Grain Size, mm, Approx	Permeability cm/sec	Void Ratio[2]	Porosity[3]
Gravel and coarse sand	0.5 and over	10^{-1} and over	0.6-0.8	0.375-0.45
Medium and fine sand	0.1 to 0.5	10^{-1} to 10^{-3}	0.6-0.8	0.375-0.45
Very fine sand and coarse silt	0.05 to 0.1	10^{-3} to 10^{-5}	0.6-0.9	0.375-0.5
Coarse and fine silt	0.05 and less	10^{-5} to 10^{-7}	0.6 up	0.375 up

[1] Additional information on other media is given in para 4-3a.
[2] The volume of voids with a soil mass divided by the volume of solids.
[3] The volume of voids divided by the total volume.

(5) Determination of the permeability of the in situ soil or rock. The general geology of the area should be known, specifically, in fractured rock, the size, configuration, and location of openings; coatings on the surface of the openings (which may affect bonding); amount of free water or moisture present (which may also affect bonding); and the strength of the medium to be grouted (which may affect grouting pressures employed).

(6) Information about the strength that can be developed in grouting fractured rock or concrete to establish whether chemical grouting will be a satisfactory approach. In some circumstances, tests may be required to show that sufficient strength can be developed to justify using the more expensive chemical grouts rather than cement grout. The openings in the fractured medium must be sufficiently large and, for the most part, well-connected to permit injection of the grout. The selection of a particular chemical-grouting system normally requires laboratory tests.

(7) Evaluation of cementitious versus chemical grouting (pros and cons of each for the site).

b. Factors affecting grouting operations.

(1) Certain factors affect grouting operations, and data regarding these factors should be obtained as follows:

(a) Physical characteristics of medium to be grouted.

(b) Temperature, both ambient and in the area to be grouted.

(c) Physical and chemical properties of grout solutions.

(d) Compatibility of chemical grout properties with physical, chemical, biological, and regulatory environments at the site.

(e) Grout hole size and spacing.

(f) Methods of drilling and cleaning.

(g) Methods of grout application.

(2) The chemistry of the medium to be grouted and of the mixture and groundwater probably influences chemical grouting more than any other factor. Chemical and physical analyses should be made of the material to be grouted and of the mixture water and groundwater prior to field grouting. Tests of the mixture water will indicate its suitability for the particular system being used (i.e., effect on gel time, strength, etc.); tests of the groundwater will indicate its effect on the grout after injection. Most chemical grouts can be formulated to meet specific requirements if the makeup and approximate quantities of the chemicals in the medium and water are known.

(3) Among the properties of chemical grout solutions that materially affect injection are the initial viscosity and the viscosity throughout the injection period; however, performance, not viscosity, should be used as the final criterion for selecting one grout over the other.

(4) The method of drilling is an important factor affecting grout injection. Drilling with circulating water in the hole will remove cuttings from the hole and keep the hole walls flushed of cuttings that would otherwise form occlusions during grouting. Clean drill holes are essential in grout rock.

c. Additional information. Information that may be helpful in planning and executing chemical-grouting operations includes the following:

(1) In dry granular materials, gravitational and capillary forces act to disperse injected grout, and the extent of this dispersion may be sufficient to render the gel ineffective. Excavations in test areas are needed.

(2) Granular materials below the water table can probably be more effectively stabilized than a dry mass.

(3) The decrease in permeability of rocky soil after stabilization depends upon the resistance of the gelled grout to extrusion from the pores in the mass. If penetration into a granular mass is appreciable, the gel cannot be extruded from pores at pressures less than the pumping pressures required to place the solutions; the pumping pressure should always exceed the static water head at the point of placing.

(4) Groundwater will displace grout in the direction of flow. In uniform formations of fine-grained materials, the rate of groundwater flow is generally so small that its effects will be negligible for most injection rates. Short gel times should be used, for instance, in medium-to-coarse sands where there is or is suspected to be an appreciable groundwater flow. Where the rate of groundwater flow is appreciable, a gel time as short as possible with a pumping rate as high as possible consistent with pressure limitations should be used. The chances of a

successful job are lessened if the rate of groundwater flow exceeds the rate at which grout can be placed.

4-3. Laboratory Testing

Laboratory tests should be conducted prior to commencing any field operations including small-scale field tests. This will eliminate delays in completing the job. In some instances, it may be advisable to conduct certain tests not necessarily dictated by the immediate problem in the event unusual situations arise. Laboratory tests include those for compressive strength, permeability, and gel time.

a. Selection of a chemical grout.

(1) In the selection of a chemical grout, it should be kept in mind that chemical grouts are generally more expensive than portland-cement grouts; however, some of them will develop a greater tensile strength, a better bond, and a higher compressive strength, depending upon the medium being grouted. Chemical grouts generally have the ability to penetrate smaller openings than cementitious grouts; however, special care should be taken in selection because of the cost. Consideration should be given to performing the grouting operation by employing a combination of alternating or concurrent cementitious and chemical grouting, if possible, for economy reasons. Also, from the standpoint of economy, cementitious grout should be used in lieu of chemical grout where possible.

(2) The physical properties of the medium to be grouted need, in some instances, to be known and matched as closely as possible. For instance, some chemical grouts bond poorly to wet or moist surfaces. The bond to wet or moist surfaces would probably be no greater than bond through the grouted mass and would probably be weaker because of dilution of the chemical grout at the interface or incompatibility of the grout with moisture.

(3) Cracks in concrete as narrow as 0.05 mm have been grouted with chemical grout, whereas portland-cement grouts are usually limited to use in 1.5-mm or larger openings. Cracks as small as 0.7 mm are also reported to have been grouted with a neat portland-cement grout. It has been reported that the lower limit for neat portland-cement grout penetrability is no finer than the 600-μm sieve. Figures 4-1, 4-2, and 4-3 and Table 4-2 show comparisons of grout types with respect to penetration characteristics, a viscosity-percent concentration

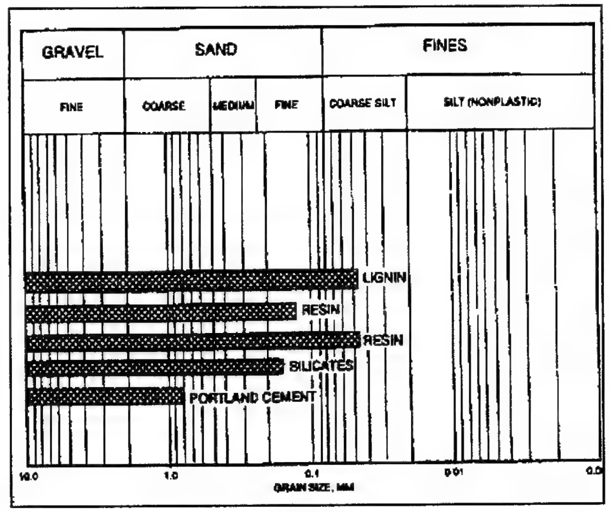

Figure 4-1. Comparison of methods for stabilizing soils and relative penetration ability

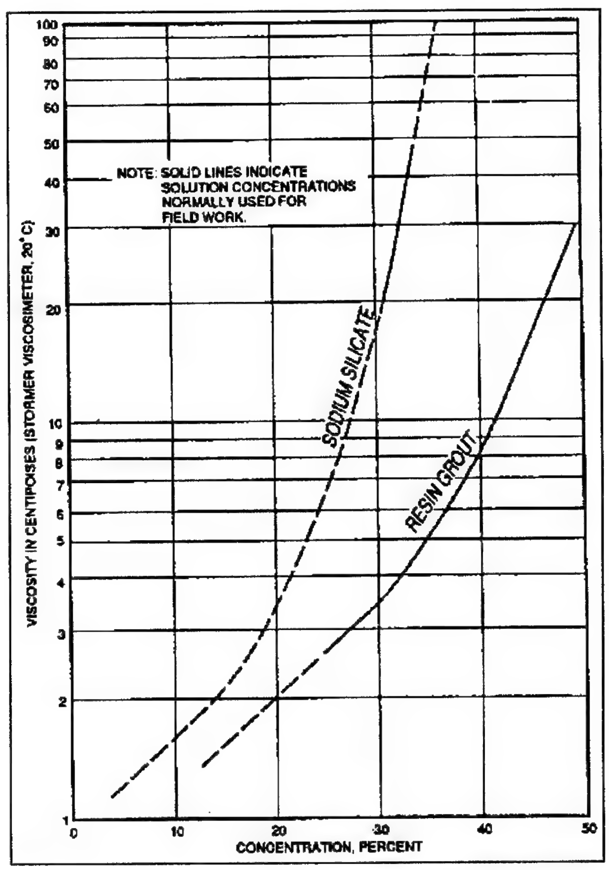

Figure 4-2. Viscosities of various grouts

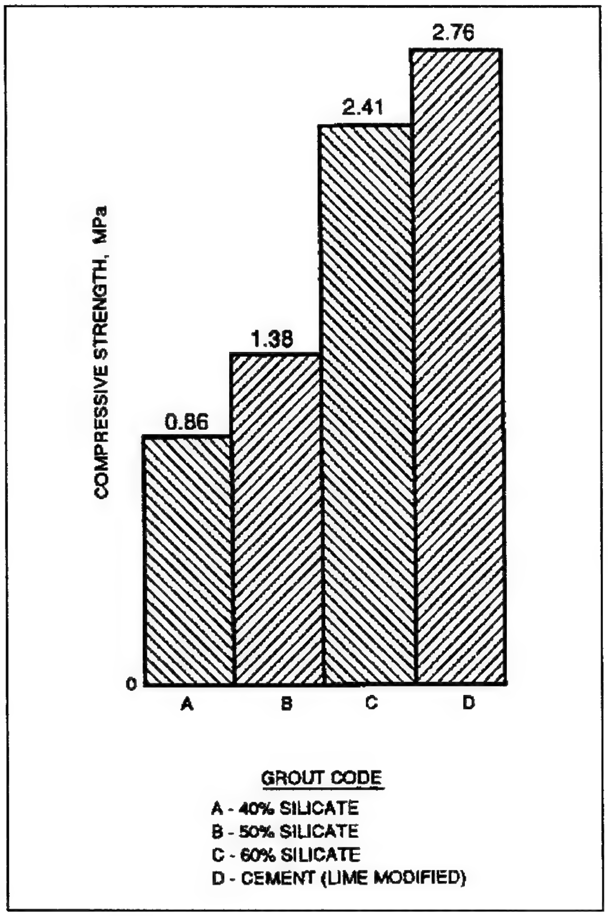

Figure 4-3. Comparison of compressive strengths of chemical grouts injected into medium-fine, wet compacted sand, injected and cured wet (adapted from Raymond International, Inc. 1957)

relation, a comparison of compressive strengths, and physical properties of chemical grouts, respectively.

b. Grouting patterns.

(1) Normally, several injection pipes or locations are used to inject chemical grout. The grouting pattern involves both the location of the pipes and the order in which the grout is placed. General criteria dictate that the sequence of injections should be performed so that the area initially grouted confines the areas to be treated by subsequent treatments, a minimum of two circles of holes are generally required for complete overlapping in circular patterns dependent upon hole spacing and the material being grouted, and three rows of holes are generally required for complete overlapping for linear patterns such as cutoff walls.

(2) In the grouting of granular materials, the injection locations should be based on the average diameter of a stabilized column, computed from the volume to be pumped and the void ratio (Figures 4-4 and 4-5). A distance slightly less than the average diameter should be used as the grid spacing. This spacing arrangement should satisfactorily seal even pervious strata. Injection pressures for the final injection should be anticipated to be higher than those required for previous work.

(3) When stratified deposits are grouted, a minimum of three rows of injections is generally required so that the confining effects of adjacent stabilized masses force subsequent injections into less pervious areas. Short gel times should also be used. With short gel times, the gelation occurs below the bottom of the pipe at all elevations, which eliminates the possibility of pumping all the solution from one injection into one stratum because the gel time and the location of the bottom of the pipe are known. The gel times need to be adjusted for changing pipe elevations.

c. Factors influencing injection methods. The material to be grouted influences the injection method to be used. Packers cannot be used satisfactorily in formations that are not competent and that will not maintain an open hole. In this instance, the formation itself acts as a seal to

Table 4-2
Physical Properties of Chemical Grouts

Class	Example	Viscosity cPs	Gel Time Range min	Specific Gravity	Strength kPa
Silicate (low concentration	Silicate-bicarbonate	20	0.1-300	1.02	Under 345
Silicate (high concentration)	Silicate-chloride	4-40 30-50	5-300 0	1.10 --	Under 3,450 Under 3,450

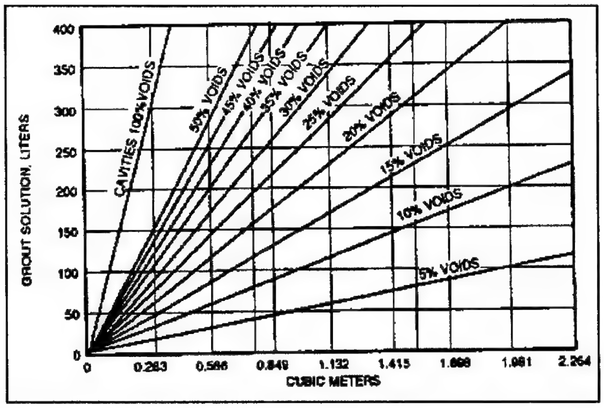

Figure 4-4. Stabilized volume in grouted medium related to grout volume (adapted from Raymond International, Inc. 1957)

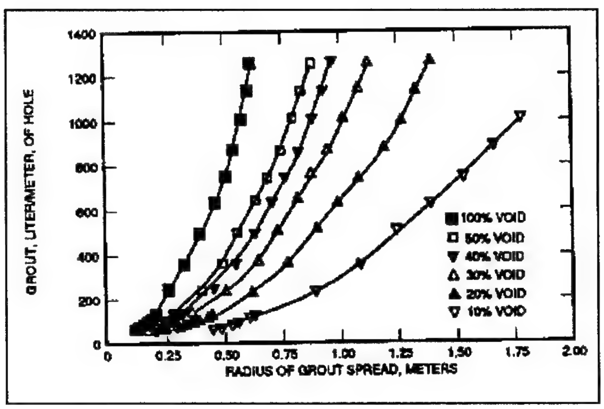

Figure 4-5. Penetration related to grout volume and percent voids (adapted from Raymond International, Inc. 1957)

prevent grout from returning along the path of the injection pipe. However, if a packer is required in an unstable open hole, the location at which the packer is desired may be grouted to form a fast-setting grout plug, the plug drilled to be a diameter to accommodate the packer, and the packer subsequently emplaced downhole at this location. Where formations will maintain an open hole, various arrangements of packers may be used.

d. Estimating quantities.

(1) In estimating chemical quantities and costs for a grouting operation, the physical dimensions of the volume of medium to be grouted and its porosity or void ratio can be used to compute the volume of grout needed for an application. Computations are most likely to be inaccurate because of the use of erroneous void ratios. The following points should be considered when establishing values of void ratio:

(a) Granular, noncohesive deposits will have, depending upon the relative density, void ratios generally between 0.6 and 0.9.

(b) Cohesive deposits will not generally accept grout.

(c) Silts of an organic nature may not accept grout.

(d) In some deposits, only the coarser strata or pockets may accept grout.

(e) In fractured rock formations, only the larger channels may accept grout. The actual fractional volume of voids should be adjusted to the percent voids that will accept grout for the purpose of computing grout volumes (Figures 4-4 and 4-5). Grout volumes for a particular job should also include a contingency for waste and dilution.

(2) When grouting through a hole where the grout pipe is to be raised or lowered at intervals, the volume of grout per specified length should be computed so that this information, in conjunction with the void ratio, can be used to compute the size of the grouted mass. Viscosity of the grout affects the time-rate of spread from one hole.

(3) Figure 4-4 shows grout quantities required to fill various void contents and is based on total fill. However, this ideal situation of total fill is seldom reached, and, as an example, it has been determined that 330 to 440 L/m^3 is an approximate quantity for injection into unconsolidated granular materials with about 35-percent voids, such as medium to fine sand.

(4) Figure 4-5 can be used in calculating quantities of grout for grouting in vertical holes.

e. Cost.

(1) The cost to prepare a given volume of chemical grout solution will vary with the different chemical grouts and the concentration of ingredients used. Three factors used to compute a cost estimate for purchasing include a total known volume, a known groutable void ratio, and a certain chemical concentration.

(2) Figures 4-4 and 4-5 can be used to estimate not only volume but also cost.

f. Economic considerations.

(1) Economic considerations in chemical grouting include the initial cost of materials, location of jobsite, quantities of grout to be used, type of materials (liquid or powder) to be shipped, and volume to be placed. Generally, the more grout that is used, the lower the unit price. Labor, overhead, and equipment rental are other influencing factors as well as the cost of drilling the grout holes.

(2) In the event an open hole remains after chemical grouting, the hole could be backfilled with a portland-cement grout mixture, which would, in most instances, somewhat reduce the overall cost. Portland cement and sand are usually available at most construction sites.

4-4. Field Operations

a. Field procedures.

(1) An important aspect of field planning is the selection of specific techniques for use. A technique for cutting off surface backflow in shallow placement operations uses a short gel time in combination with controlled on-and-off pumping cycles. Unfortunately, short gel times may also result in gel formation in areas that would seal off the mass being treated against further treatment. When surface backflow is first observed, the pumps are kept running until it is certain that the material produced is true chemical grout. Dyes can be helpful in distinguishing the chemical grout from water or some other solution. The grout running out at the surface is checked for gel time, and the gel time of a new solution is shortened. The pumps are then shut off for a length of time equal to half that of the gel time. When the pumps are turned on again, if backflow reoccurs, the pumps are kept running until sufficient chemical has been pumped to clear the pipe or hole, and the pumps are then shut down for a length of time equal to three-fourths that of the present gel time. When pumping is again resumed, if seepage starts again, the procedure is repeated, but the pumps are restarted at a lower rate. In order to use this method without plugging the hole, the actual gel time must be known.

(2) Gel times shorter than pipe-pulling time have been successfully used. This is of benefit in stratified deposits where pumping pressure limitations permit and also where following water is present. Gel times as short as practical should be used to prevent the grout from being carried away by groundwater and to seal more pervious areas, thus forcing grout into the finer material. Injection efficiency in stratified deposits would naturally be decreased with a gel time increase in this instance.

(3) The desired results of a field grouting program are most readily obtained if the size and shape of a grouted mass can be predicted. Heterogenous stratification and flowing groundwater modify the end result.

(4) Grout injected from a point within a mass of uniform permeability, as in a sand mass, can be expected to flow out from the injection point to form a sphere. This is normally true if the grout injection pressure is greater than the static head and if the volume is small so that the hydrostatic pressures at top and bottom of the mass are not significantly different. The rate at which grout is placed, the rate of groundwater flow, and the gel time determine the displacement and final configuration of the grout mass.

(5) Injected grout will seek the easiest flow paths. The only factors that can be introduced to modify this condition are control of the setting time and, in some instances, a change in viscosity. Accurately controlling the gel time is also important in stratified deposits. If the permeability between the horizontal and vertical directions differs due to either placement or stratification, as is frequently the case, better control can be obtained if the grout is formulated to set up at the instant when the desired volume has been placed where water may be flowing. With gel times shorter than pumping times, the grout pumped last is farthest from the injection point by virtue of being forced through previously gelled grout. If the location of this point is known and if the grout gels at this location, then the grout mass location is known.

(6) After a grout or grouts have been selected, a small-scale field test should be performed as a final step in deciding which grout to use.

b. Physical properties. In general, granular materials or rock masses with overall permeabilities of 1×10^{-7} cm/sec or less cannot be economically grouted. Included in this category are clays, very fine silts, and coarser materials containing sufficient fines to render them relatively impermeable. Formations with permeabilities of 1×10^{-5} to 1×10^{-7} cm/sec can be grouted, generally with difficulty, particularly where the formation is shallow and limited pumping pressures can be used. Noncohesive soils in this permeability range are generally classed as silts. Coarser materials with higher permeabilities can generally be grouted without difficulty.

Successful grouting of materials with low permeabilities depends primarily upon the grout selected.

c. Changes in physical properties. Chemical grouting may either harm or improve the original properties of the grouted material. Chemical grouting of granular materials may serve a dual purpose: improvement of existing properties and alteration of existing properties to form a new material. In the latter case, the chemicals in the grout react with grouted material to form a new material. The new material may or may not be an improvement. Adverse effects of chemical grouts on materials may possibly include an increase in permeability or a decrease in strength. Cyclic drying and wetting or all drying may be detrimental to a grouted area because of a breakdown of the gelled chemical grout brought about by the cycles.

d. Dilution. In general, dilution with groundwater is detrimental only when the dilution is such as to bring a quantity of grout below the concentration at which it will gel. This will occur when turbulence exists, or is created, or when a small volume of grout is injected into a large volume of flowing water and to a lesser degree of static water. These conditions are sometimes checked by the use of dye tracers to determine the extent of the dilution and the effectiveness of countermeasures. Generally speaking, water-based chemical grouts will dilute to varying degrees depending upon the conditions mentioned above.

e. Penetration. Grouts that have a viscosity of 2 cP will penetrate at half the rate of water (1 cP) at equal pressure or require double the pressure to obtain rates equal to that of water. Thus, viscosity differences are significant in the range approaching the viscosity of water. Other conditions being equal, the rate at which chemical grouts can be pumped into a formation will vary inversely with the grout viscosity and directly with the pumping pressure.

4-5. Grout Availability

Chemical grouting is a rapidly changing field due to both technological and regulatory advances. New products are being introduced onto the market, and older products are being withdrawn. In order to determine what is currently being offered by vendors, it is necessary to consult trade and industrial directories and current periodicals and technical journals. The best sources of current data are the manufacturers, suppliers, and their most recent clients.

Appendix A
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Appendix B
Glossary

B-1. Terms

accelerator - chemical admixture that increases the rate of a chemical reaction.

activator - chemical admixture that activates a catalyst to begin a reaction.

admixture - materials other than water, fine aggregate, or hydraulic cement used as an component in grout.

aggregate - granular mineral material such as sand, ground slag, or rock that is used as fine aggregate and mixed with water and cement to form a grout.

aquifer - subsurface stratum or zone capable of producing water as from a well or spring.

base - primary component in a grouting system.

batch system - injected method in which all of the grout components are mixed at one time prior to injection.

bearing capacity - maximum unit load a soil mass or rock mass will sustain without excessive settlement or failure.

bentonite - clay containing 75 percent or more of smectite characterized by its large volume increase on wetting.

bond strength - measure of the adherence of grout to other materials in contact with it.

carcinogenic - substance or agent that produces or tends to produce cancer.

catalyst - compound that increases the speed of a reaction but remains unchanged.

catalyst system - combination of compounds (an initiator and an accelerator) that cause a chemical reaction to begin and promote the reaction after initiation.

chemical grout - see **grout, chemical.**

coefficient of permeability - velocity of laminar flow (centimeters per second) through a unit cross-sectional area of a porous medium under unit hydraulic gradient at a standard temperature.

coefficient of transmissivity - flow rate through a unit width vertical strip of an aquifer under a unit hydraulic head.

colloid - substance (usually a liquid) composed of finely divided particles that do not settle out of suspension.

colloidal grout - see **grout, colloidal.**

concrete, preplaced aggregate - concrete produced by placing coarse aggregate in forms and filling the voids with a cementitious grout.

cure time - time elapsed between mixing the components of a grout and the development of the desired hardened properties.

curtain grouting - see **grouting, curtain.**

displacement grouting - see **grouting, displacement.**

emulsion - liquid containing a second dispersed phase composed of minute droplets of liquid.

epoxy resins - multicomponent resin consisting essentially of epoxide groups that is characterized by very high tensile, compression, and bond strengths.

fault - rock fracture along which observable displacement has occurred.

fines - soils or granular material with a nominal size smaller than 0.075 μm.

fissure - fracture in a rock or soil mass.

fracture - fissure or break in a rock mass that may be a natural consequence of folding or faulting or artificially produced by pressure injection.

fracturing - intrusion of grout along cracks or fissure at pressures sufficient to move the crack surfaces apart.

gel - condition in which a liquid grout begins to develop strength.

gel time - time interval elapsed between the mixing of a fluid grout and the formation of a gel.

grout - substance that has sufficient fluidity to be injected or pumped into a porous body or into cracks and is intended to harden in place (see **grout, cementitious**; **grout chemical**, etc.).

grout, cementitious - mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents; also a mixture of other composition but of similar consistency. (See also **grout, neat cement** and **grout, sanded.**)

grout, chemical - solution injected into a porous body or a crack that reacts in place to form a gel or solid.

grout, colloidal - grout in which a substantial proportion of the solid particles have the size range of colloid.

grout, epoxy - grout which is a mixture of commercially available ingredients consisting of an epoxy bonding system, aggregate or fillers, and possibly other materials.

grout, field-proportioned - hydraulic-cement grout which is batched at the jobsite using water and predetermined portions of portland cement, aggregate, and other ingredients.

grout, hydraulic-cement - grout which is a mixture of hydraulic cement, water, and other ingredients, with or without fine aggregate.

grout, machine base - grout which is used in the space between plates or machinery and the underlying foundation and which is expected to maintain essentially complete contact with the base and to maintain uniform support.

grout, neat cement - fluid mixture of hydraulic cement and water, with or without other ingredients not including fine aggregate; also the hardened equivalent of such mixture.

grout, preblended - hydraulic-cement grout that is a commercially available mixture of hydraulic cement, aggregate, and other ingredients which requires only the addition of water and mixing at the jobsite; sometimes termed pre-mix grout.

grout, sanded - grout in which fine aggregate is incorporated into the mixture.

grout header - pipe assembly attached to the grout hole through which grout is injected.

grout take - amount of grout injected into a soil or rock formation, determined by measuring the volume of grout placed per unit volume of formation.

grout slope - natural slope of fluid grout injected into preplaced-aggregate concrete.

groutability - degree to which a soil or rock unit can be grouted.

grouted-aggregate concrete - see **concrete, preplaced-aggregate.**

grouting - process of filling with grout. (See also **grout.**)

grouting, advancing-slope - method of grouting by which the front of a mass of grout is caused to move horizontally through preplaced aggregate by use of a suitable grout injection sequence.

grouting, closed-circuit - injection of grout into a hole intersecting fissures or voids which are to be filled at such volume and pressure that grout input to the hole is greater than the grout take of the surrounding formation, excess grout being returned to the pumping plant for recirculation.

grouting, containment - see **grouting, perimeter**.

grouting, contraction-joint - injection of grout into contraction joints.

grouting, control-joint - see **grouting, contraction-joint**.

grouting, curtain - injection of grout into a subsurface formation in such a way as to create a zone of grouted material transverse to the direction of anticipated water flow.

grouting, displacement - grouting that is done in order to physically move the solid material adjacent to the point of grout injection.

grouting, high-lift - technique in concrete-masonry construction in which the grouting operation is delayed until the wall has been laid up to a full story height.

grouting, low-lift - technique of concrete-masonry wall construction in which the wall sections are built to a

height of not more than 5 ft (1.7 m) before the cells of the masonry units are filled with grout.

grouting, open-circuit - grouting system with no provision for recirculation of grout to the pump.

grouting, penetration - grouting that is done to fill in the void spaces between solid particles without forcing the particles apart.

grouting, perimeter - injection of grout, usually at relatively low pressure, around the periphery of an area which is subsequently to be grouted at greater pressure; intended to confine subsequent grout injection within the perimeter.

grouting, slush - distribution of a grout, with or without fine aggregate, as required over a rock or concrete surface which is subsequently to be covered with concrete, usually by brooming it into place to fill surface voids and fissures.

grouting, stage - sequential grouting of a hole in separate steps or stages in lieu of grouting the entire length at once.

hardener - component in an epoxy or resin grout that causes the base material to cure to a solid.

hydrostatic head - fluid pressure measured by the height of water above a stated level.

inert - material that does not participate in a chemical reaction.

inhibitor - material that slows the rate of a chemical reaction.

Joosten process - chemical-grouting process using sodium silicate solution and a concentrated salt (electrolyte) solution generally as a two-step process.

Malmberg system - grouting system based on addition of sodium silicate solution and weak acids.

material safety data sheet (MSDS) - formal document furnished by a manufacturer that states in detail all safety concerns in using or disposing of a product.

metering pump - pump that allows separate components of a grout to be dispensed in any desired proportion or in fixed proportions.

mutagenic - substances that can produce genetic damage that becomes apparent in offspring.

Newtonian fluid - fluid that shows a constant velocity under different rates of shear.

packer - device inserted into a grout hole that expands mechanically or by inflation to restrict the flow of grout to a specific part of the grout hole.

penetrability - property of a grout that describes its ability to fill up a porous mass.

penetration grouting - see **grouting, penetration**.

permeability - property of a porous material that indicates the rate at which a liquid can flow through the pore spaces.

pH - measure of the hydrogen ion concentration in a solution; values below pH 7.0 indicate acid solutions; values above pH 7.0 indicate alkaline solutions.

porosity - percentage of a solid volume that is taken up by voids or pores.

positive displacement pump - pump that will build pressure when a pump line is closed until the pump motor stalls or the pipe fails.

reactant - in a grout, a component that interacts chemically with the base material.

refusal - point in the grouting process when the resistance of the formation is equal to the pressure developed by the injection pump so that grout flow ceases.

retarder - grout component that slows the rate at which chemical reactions occur in the grout.

seepage - movement of a small volume of fluid through fissured rock or soil.

shelf life - maximum time a material can be stored and retain its chemical reactivity.

slabjacking - injecting grout under a concrete foundation or pavement to raise it to a desired level.

slaking - deterioration of a material (especially an aggregate) as a result of soaking in water.

stage grouting - grouting of a hole in individual steps or stages as opposed to grouting the hole in one operation.

syneresis - contraction of a gel due to loss of liquid.

time of setting - time interval between grout mixing and gelation.

toxic substances - substances that are poisonous.

unconfined compressive strength - stress (load per unit area) at failure of a cylindrical specimen subjected to axial loading without lateral or confining stress.

uplift - vertical displacement of a formation due to grout injection.

viscosity - internal resistance of a liquid to flow.

void ratio - ratio of the volume of voids in rock or soil to the volume of the rock or soil mass.